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Soldiers operating in the desert wearing body armor and other heavy clothing cannot adequately dissipate heat. Both physical and mental functions are impaired when body core temperature increases. Performance can be enhanced and health risks reduced with the aid of the body core cooling device being developed in this program. The development described here builds on successful demonstrations by Heller et al. at Stanford University, which showed that heat can be extracted from the body core through the palm of the hand - up to 65 W for individuals with vasodilation and mild hyperthermia. In the present DARPA-sponsored research program, Physical Sciences Inc. (PSI) began the engineering of a practical hand cooling device that could be deployed in combat vehicles. The report describes an engineering thermal analysis of the hand, calorimetry experiments, and the design and testing of a thermoelectric hand cooling device representative of a device that might be deployed.

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Soldiers operating in the desert wearing body armor and other heavy clothing cannot adequately dissipate heat. Both physical and mental functions are impaired when body core temperature increases. Performance can be enhanced and health risks reduced with the aid of the body core cooling device being developed in this program.

The development described here builds on successful demonstrations by Heller et al. at Stanford University[1-4], which showed that heat can be extracted from the body core through the palm of the hand - up to 65 W for individuals with vasodilation and mild hyperthermia. The existence of arterio-venous anastamoses (AVA's) in the palm allow large flow rates of blood through the palm as part of the body's thermal control system. When open, these structures shunt blood past the flow-restricting capillary vessels, rendering the hand an efficient heat exchanger. The Stanford researchers also demonstrated that a vacuum can be applied to the hand to further increase blood volume and residence time in the hand, compounding the release of heat through the palm. Palmar heat transfer would be particularly useful for soldiers in combat gear, because the palms and the face are the only skin surfaces not covered.

In the present DARPA-sponsored research program, Physical Sciences Inc. (PSI) began the engineering of a practical hand cooling device that could be deployed in combat vehicles such as the Bradley Fighting Vehicle or the Stryker. Described below are an engineering thermal analysis of the hand, calorimetry experiments, and the design and testing of a thermoelectric hand cooling device.

Our experimental results show that most of the benefit of hand cooling can be obtained without the vacuum. For short-term cooling of overheated persons, a pair of devices (one for each hand) would provide more total heat transfer than a vacuum-augmented single-hand cooler.

The solid-state cooler design is suitable for installation on an armored transport vehicle. For an 80 Kg soldier with an estimated body core mass of 10 Kg, a 30 W cooler could provide a cooling rate of 3 deg/hr, reducing the adverse thermal effects on soldiers and enhancing their ability to perform their jobs.

2. Heat Transfer Modeling

The transfer of heat from the body core involves several steps. We have modeled the two primary internal steps, as shown in Figure 1. The first step is the convection of heat into the hand through blood flow. The second is conduction through the dermis of the hand from the blood vessels to the cold surface.

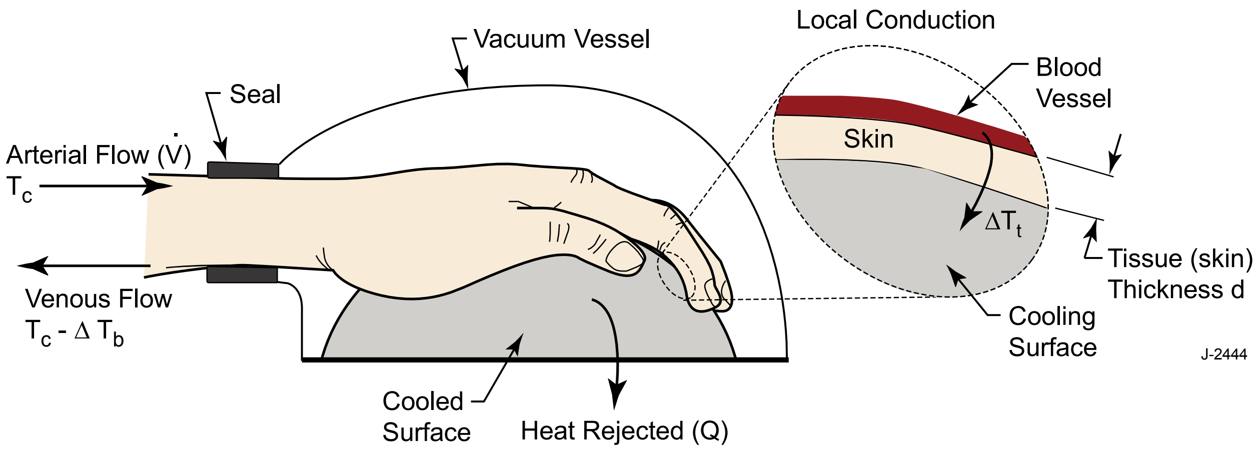

Figure 1. Cooling glove concept, indicating two primary modes of heat transfer: Convection of blood and conduction through skin.

The heat Q_{conv} carried to the hand through convection of blood is characterized by the blood flow rate and the temperature change of the blood as it passes through the hand. Specifically,

$$Q_{conv} = c_v \dot{V} \Delta T \tag{1}$$

The volumetric specific heat of blood (c_v) has a value of 3.6 J/ml-C. The blood flow rate to the hand $\dot{V}$ is typically about 1.4 ml/sec at rest. This was estimated from the measurements of flow velocities made by Doppler Ultrasound [4,5]. The referenced article indicates that flow velocities in the radial and ulnar arteries in resting individual are approximately 12 cm/s. The typical diameters for these vessels are 2.5mm for the ulnar and 3.1mm for the radial artery [6,7].

For an exercising individual under heat stress, the cardiac output increases to more than twice the resting rate (from 6 l/min at rest to more than 13 l/min). We have not seen conclusive evidence of the path for the additional flow, though Stanford researchers believe that much of the additional flow is directed into the hands, feet, and parts of the head – all places rich in AVAs. The flow to the hands could thus increase by a factor much greater than two under these physiologic conditions.

If we assume a flow rate of 3 ml/sec, then to achieve 68W of heat transfer in Eq. (1), the change in blood temperature through the hand must be 6.3 deg.

Next, consider conduction through the tissue. A simple conduction model for heat flow through a layer is

$$Q_{cond} = kA\Delta T / d \tag{2}$$

This model describes 1-dimensional flow through a layer of thickness of *d* and cross-sectional area of *A*, with a temperature difference across the layer of ΔT .

Based on typical dermal dimensions on the palmar surface, we assumed that the cold surface is 2mm from the blood vessels. From approximate measurements of the hand of one of our investigators, we estimated a heat transfer area of 120 cm^2. The thermal conductivity of skin varies from layer to layer, but a representative mean value is 0.004 W/cm-K.

If the blood enters the hand at 37C and leaves at 37C-6.3C, the mean temperature of blood in the hand is approximately 33.9C. If the cold surface of the cooling device is 10C, dT=23.9C and the heat transfer through the tissue is 58W (from Eq. (3)). This is not far from the heat transfer rates measured by Stanford researchers.

3. Experimental Apparatus

Figure 2 shows the laboratory set-up for PSI's experiments. At the time we began this project, calorimetry experiments had not been completed at Stanford or made available, and this experiment was intended to characterize the heat transfer itself rather than its effect on the core temperature.

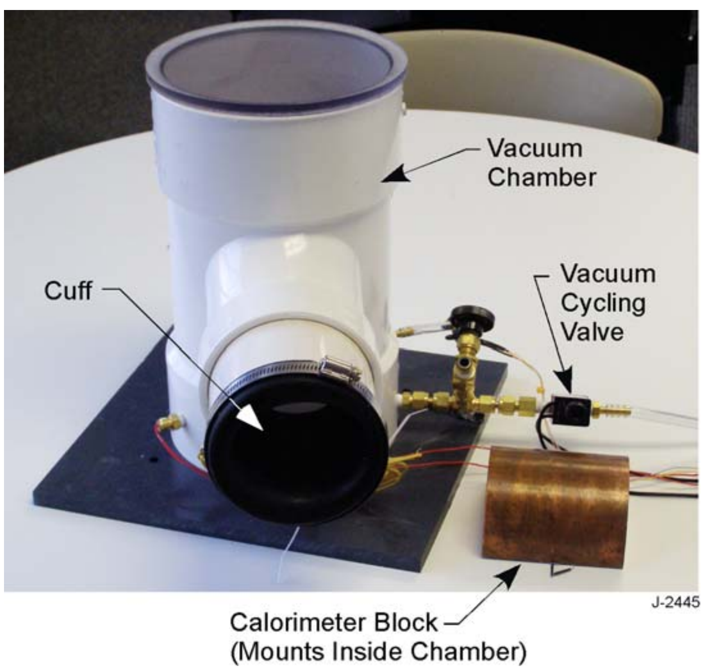

Figure 2. PSI's experimental apparatus for palmar calorimetry.

To measure the transfer from the hand, we used a large copper block as a calorimeter. A thermistor at the center of the block measured the temperature of the calorimeter. The heat transfer rate to the block is given by

$$Q = \frac{dT_{cal}}{dt} c_{cal} \tag{3}$$

where c_{cal} is the heat capacity of the calorimeter and T_{cal} is the measured temperature.

Two different calorimeter blocks were used (Figure 3). We began with a 5cm diameter block with a mass of 3.8 kg. We conducted a contact area test to determine the most effective way to grip the calorimeter. The block was covered with ink, and an investigator gripped the block. This was repeated in a few positions, as well as with a conical plastic model. The conical model had the greatest contact area with the hand (Figure 4(b)). The straight grip on the cylinder (Figure 4(a)) had a significant gap in the coverage in the center of the palm. An angled grip on the cylinder (Figure 4(c)) provided nearly as much contact as the conical model, and did not require machining of a large and complex shape.

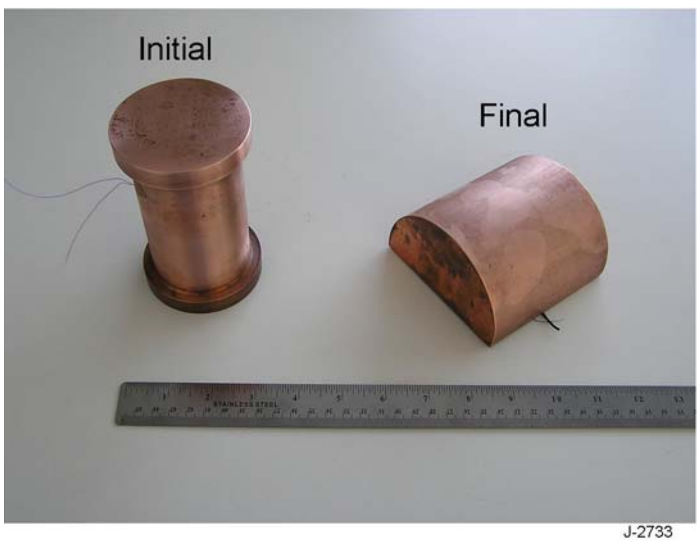

Figure 3. Two calorimeters used in PSI experiments.

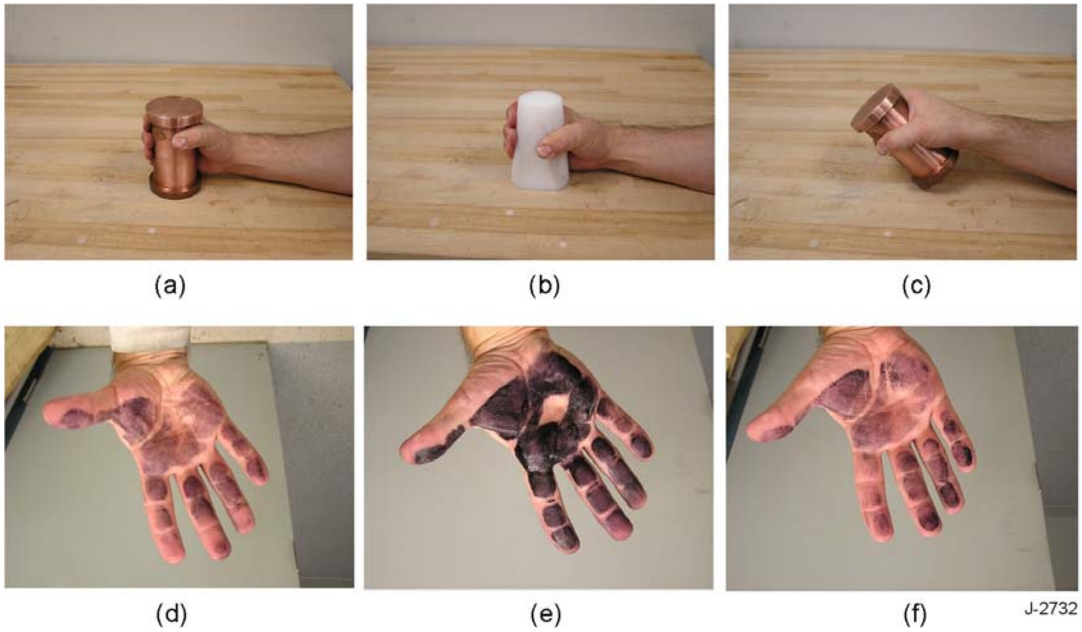

Figure 4. Ink pattern shows contact area with the calorimeter.

We learned in early experiments that, because the 5cm calorimeter allow the hand to fully encompass it, users tended to grip the copper firmly. This restricts blood flow to the skin and reduces heat transfer. Stanford researchers had reached similar conclusions and moved to a large-radius surface that could not be tightly gripped. We adopted the 10cm diameter block, which had a mass of 4 kg and a heat capacity c_{cal} of 1540 J/C.

For each test, the block was pre-cooled to a starting temperature (10C-22C) before the test subject gripped the block. To cool the calorimeter, an aluminum transfer block was cooled in ice water and then put in contact with the copper calorimeter until the temperature of the copper reached the desired level.

The block was thermally isolated from the rest of the apparatus. The parasitic loss to the environment, measured by cooling the block and observing its rate of warming, was less than 1W.

Thermal equilibrium time for the blocks was calculated and measured to be about 15 s. Typical heat extraction experiments were conducted for 300 s. Depending on the subject thermal loads, the temperature change ranged from a low of 2C to a high of 12C.

The entire apparatus was placed in a room enclosure, which was heated to 25C-28C. The test subject rode an exercise bike to increase body temperature. After a specified calorie consumption, the subject grabbed the block either with or without vacuum. A data acquisition computer logged the block temperature. Figure 5 shows the schematic for the electronic and vacuum subsystems.

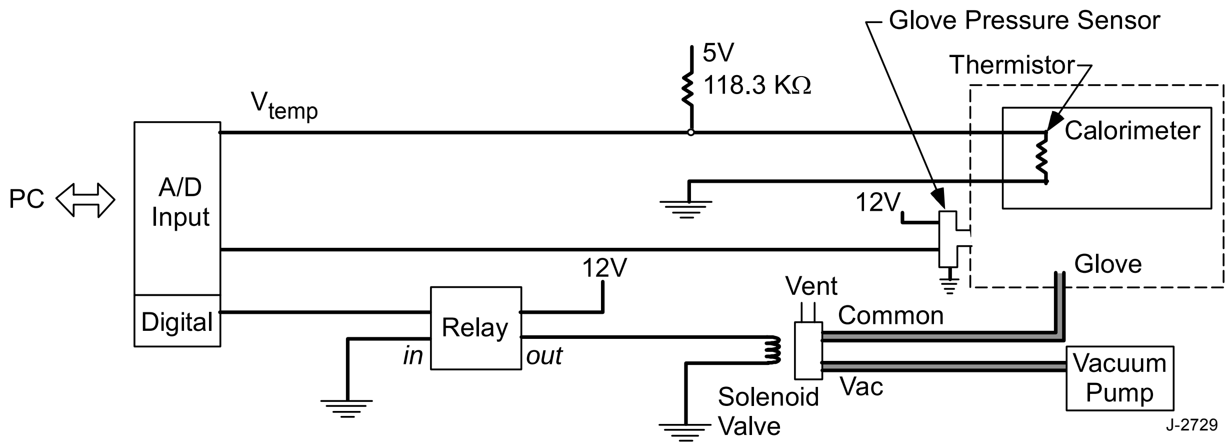

Figure 5. Schematic of control and signal acquisition.

The thermistor was a model 44030 from Omega engineering. Its resistance was measured by sensing V_{temp} in Figure 5. The voltage was converted to an equivalent resistance, and the manufacturer's calibration table was interpolated to obtain the temperature.

Figure 6 shows a typical measurement of calorimeter temperature rise during an experiment without vacuum. The RMS noise is approximately 0.5C.

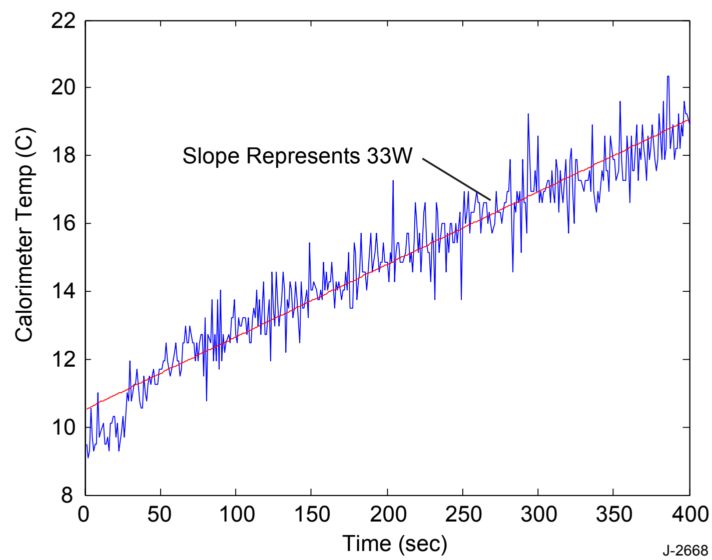

Figure 6. Typical calorimeter temperature record.

4. Results

Early experiments with the PSI device helped PSI engineers to learn to use the apparatus and make some improvements, such as the change in grip design. The earlier tests were conducted in a 21C room with subjects normothermic or slightly hyperthermic.

Once the device was functioning with the new grip, it was installed in a room that could be warmed as high as 30C. The test subject rode an exercise bike for 30 minutes at a rate that used 14 kCal/min. Then, the subject placed his hand in the glove, and the temperature was recorded for 5 minutes. In some cases, a second set of data was taken with an additional 10min exercise segment between calorimetry experiments.

For experiments where vacuum was applied, the vacuum was cycled (e.g., 15 sec on/5 sec off) throughout the test. This was accomplished by varying the position of the solenoid shown in Figure 5, so that the chamber was connected either to the pump or to vent. Figure 7 shows the measured chamber pressure.

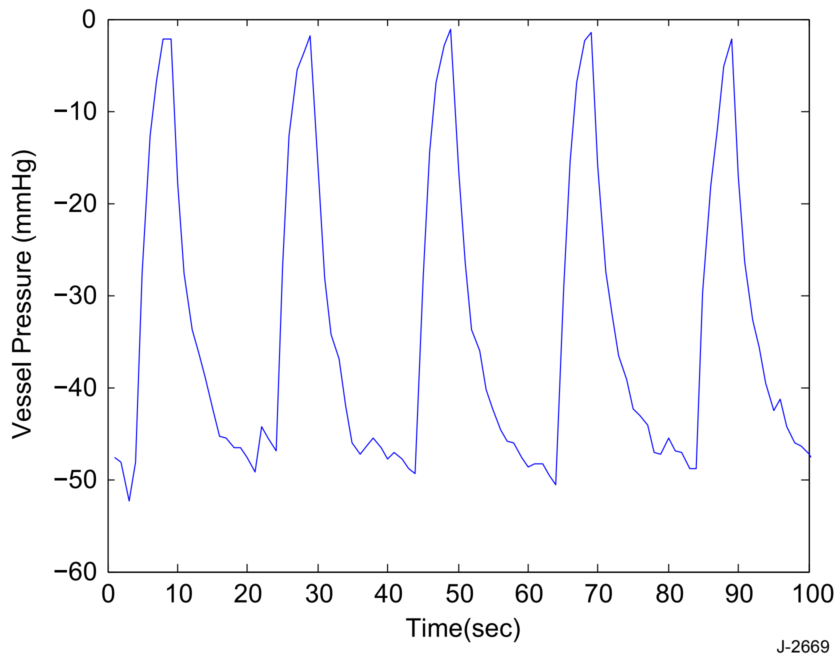

Figure 7. Vacuum was cycled during the tests wherein it was applied.

Figures 8 and 9 show results for two subjects. The plots are of the calorimeter temperature during the experiment. For subject 1 (Figure 8) there are two runs with vacuum and one without. The heat transfer rate without the vacuum was 21W. The vacuum results are very different. One case showed no change from the no-vacuum case. The other showed an increase of more that 100%. A sharp change in heat transfer is noted in this case, at 150 sec. This is typical of sudden vasoconstriction. In Figure 9, with subject 2, there is very little difference in heat transfer for the vacuum and no-vacuum cases. In this vacuum case, the vacuum was cycled 30 sec on/10 sec off. For this subject, the heat transfer achieved in the non-vacuum case was ~16W.

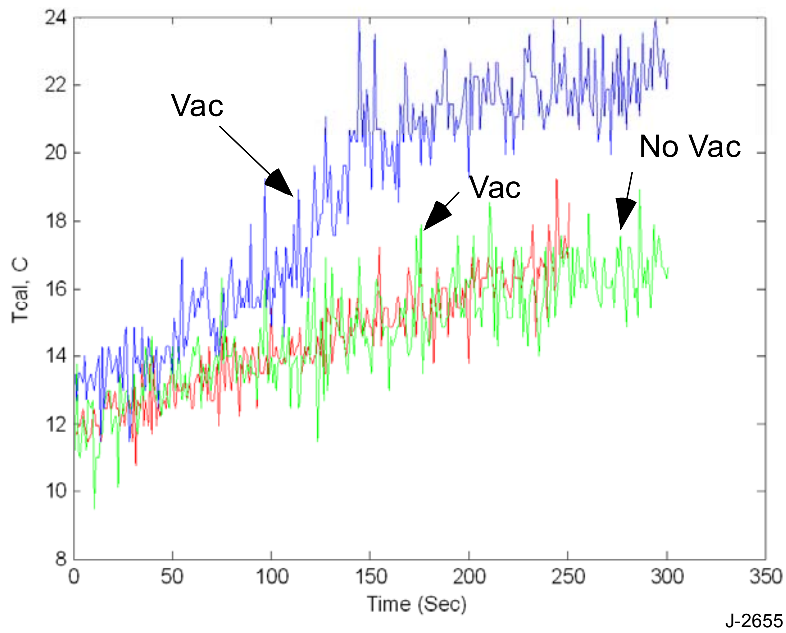

Figure 8. Calorimetry with subject 1 shows that the vacuum sometimes induces a large increase in heat transfer, and other times has no significant effect.

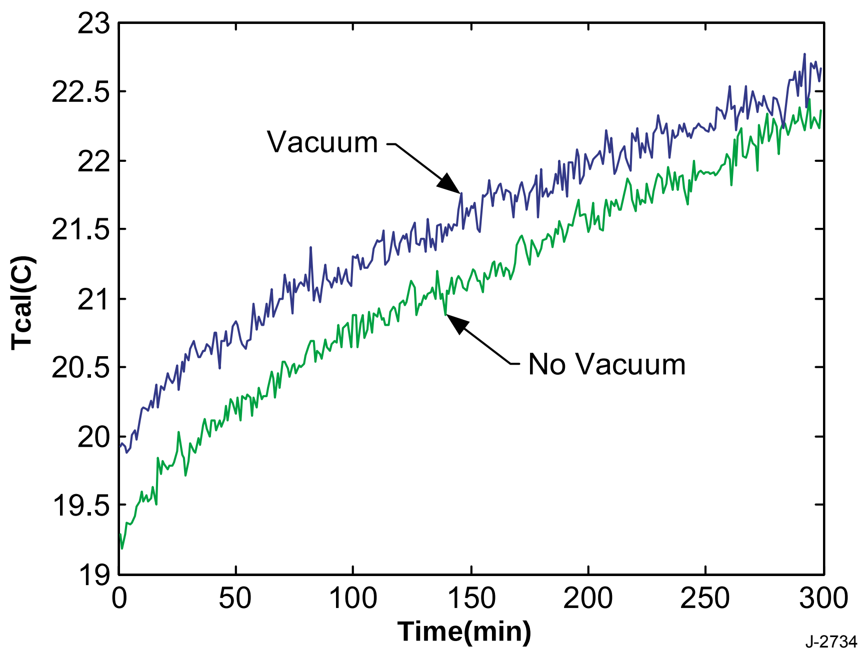

Figure 9. Calorimetry with subject 2 shows no enhancement to the slope with vacuum applied.

Other acquired data on a total of six subjects showed typical vacuum enhancements of 15%. The 15% improvement is similar in magnitude to the day-to-day variation for an individual. Some subjects showed no response to the vacuum at all.

The difference between PSI results, showing modest enhancements in heat transfer with vacuum, and Stanford's results, which show large increases, is most likely due to the difference in test conditions. The Stanford apparatus is used in a room that can be operated at 40C or more, and subjects can experience significant hyperthermic stress. This conclusion is based on conversation with the Stanford researchers, who have seen similarly modest vacuum enhancements in subjects who were not highly thermally stressed.

To check the measurements obtained in the PSI device, we tested one subject both in the PSI device and Stanford apparatus. Figure 10 shows the measurements made in the Stanford apparatus. The heat transfer data were averaged over 30-sec blocks to create the plot. These data were taken with vacuum.

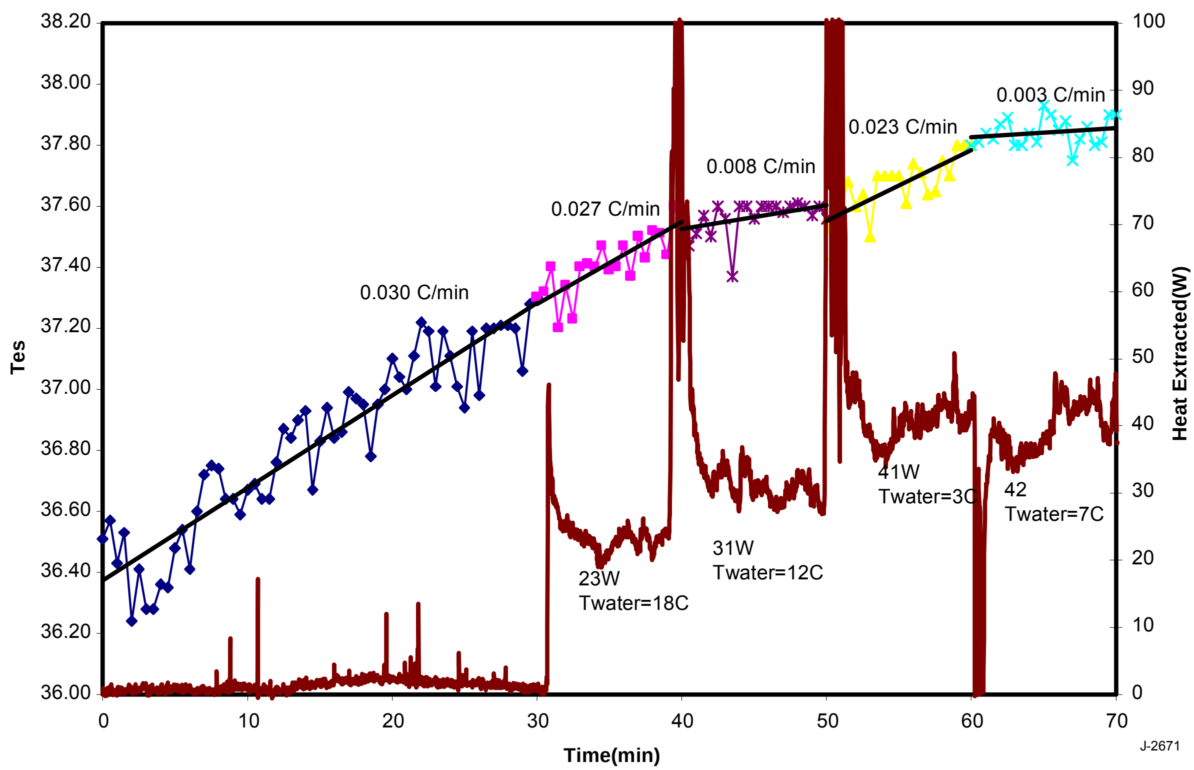

Figure 10. Measurements made at Stanford confirm the PSI calorimetry results.

The most noteworthy results are that with the 12C cooling block, the Stanford device measured a heat transfer rate of 31W. The PSI device measured a heat transfer rate of 33W for 12C. Likewise, the Stanford test measured 23W extracted for an 18C block, while tests in the PSI device measured 20W for this temperature. These measurements are sufficiently close that we determined the PSI calorimetry was matched to the Stanford device.

5. Thermoelectric Cooler Design

PSI constructed and tested a prototype hand cooler to show how a deployable device might be configured. The prototype is based on a solid-state design, requiring no compressed gases or liquids. The coolers are based on the Peltier thermoelectric effect, depicted in Figure 11.

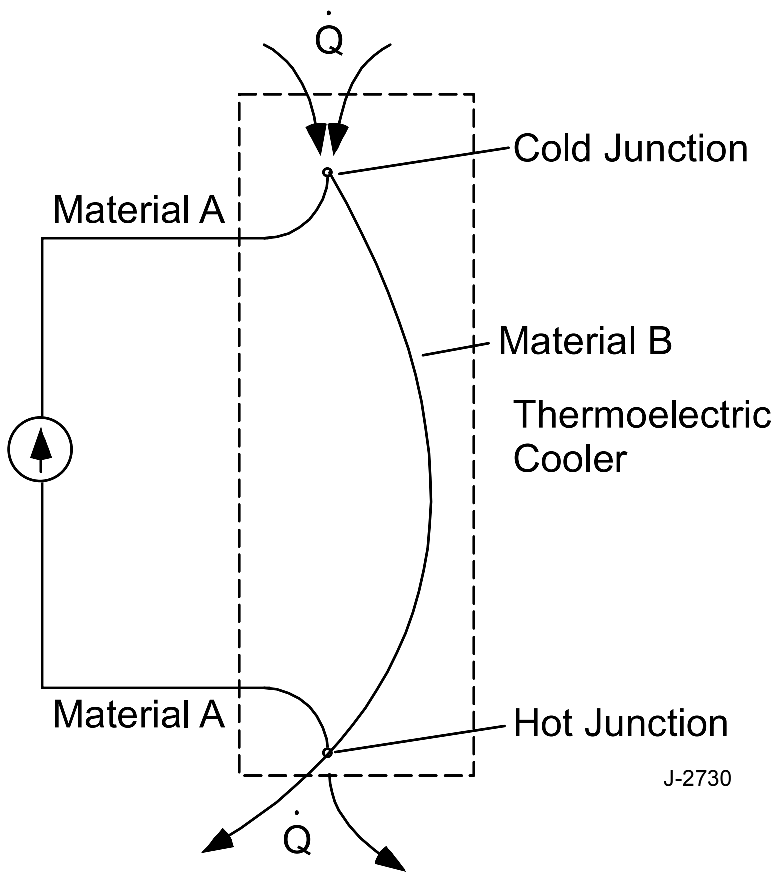

Figure 11. The Peltier thermoelectric effect.

Two junctions of dissimilar materials make up the thermoelectric cooler (TEC). Current flowing through this complimentary pair transfers heat from the cold junction to the hot junction.

Figure 12 shows a commercially-available Peltier (TEC) device produced by Melcor. This device can operate with a hot-side temperature as high as 150C, though devices that can operate at up to 225C are available from Melcor. The figure also shows the performance curves for the device. Operating in a high-temperature environment (>40C) will require hot-side temperatures above 40C to reject the heat. If sufficient heat can be rejected from a 55C hot side, the temperature difference across the heater of 45C will provide the 10C cold plate.

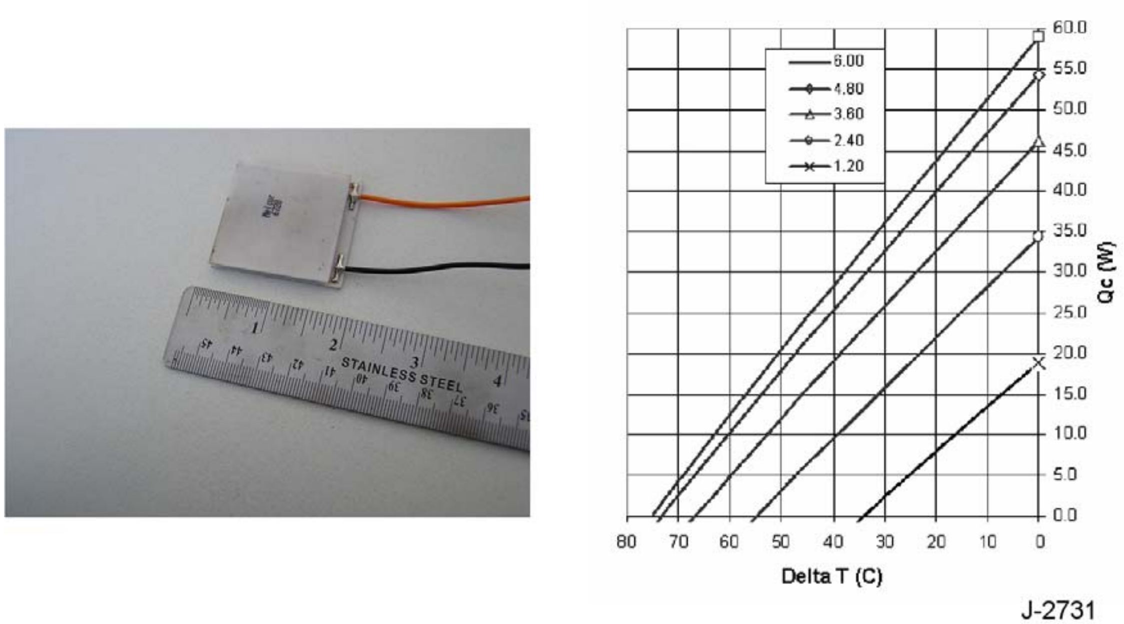

Figure 12. Melcor Model HT6-12T-4 thermoelectric cooler. Plot shows operation characteristics of the device at various currents.

From the performance chart, the heater shown here would b expected to move up to 25W with a 6A current flow. The voltage required to achieve 6A is approximately 14V, so the power consumption would be 84W. A pair of the devices would provide 50W of cooling.

If we increase the number of coolers to four and accept a lower heat transfer per cooler (15W), each heater will consume 30W. Four coolers would consume a total of 120W while providing 60W of cooling.

This example is for one commercially-available device, and higher-performance devices are available. More engineering is necessary to optimize the number of coolers, mounting of the coolers, operating conditions, and hot-side temperature.

Figure 13 shows the design of the PSI prototype built in this program. It consisted of two devices (Melcor HT6-12T-4) between aluminum plates. A pair of CPU cooling fans and associated heat sinks removes heat from the hot face. This apparatus was built with readily-available components and was not optimized. Nevertheless, we demonstrated the ability to remove 30W while maintaining a cold-surface temperature of 9C in a 22C environment. In a 35C environment, the device could maintain a 21C cold plate temperature while transferring 34W. In both of these cases, the power consumption was approximately 120W.

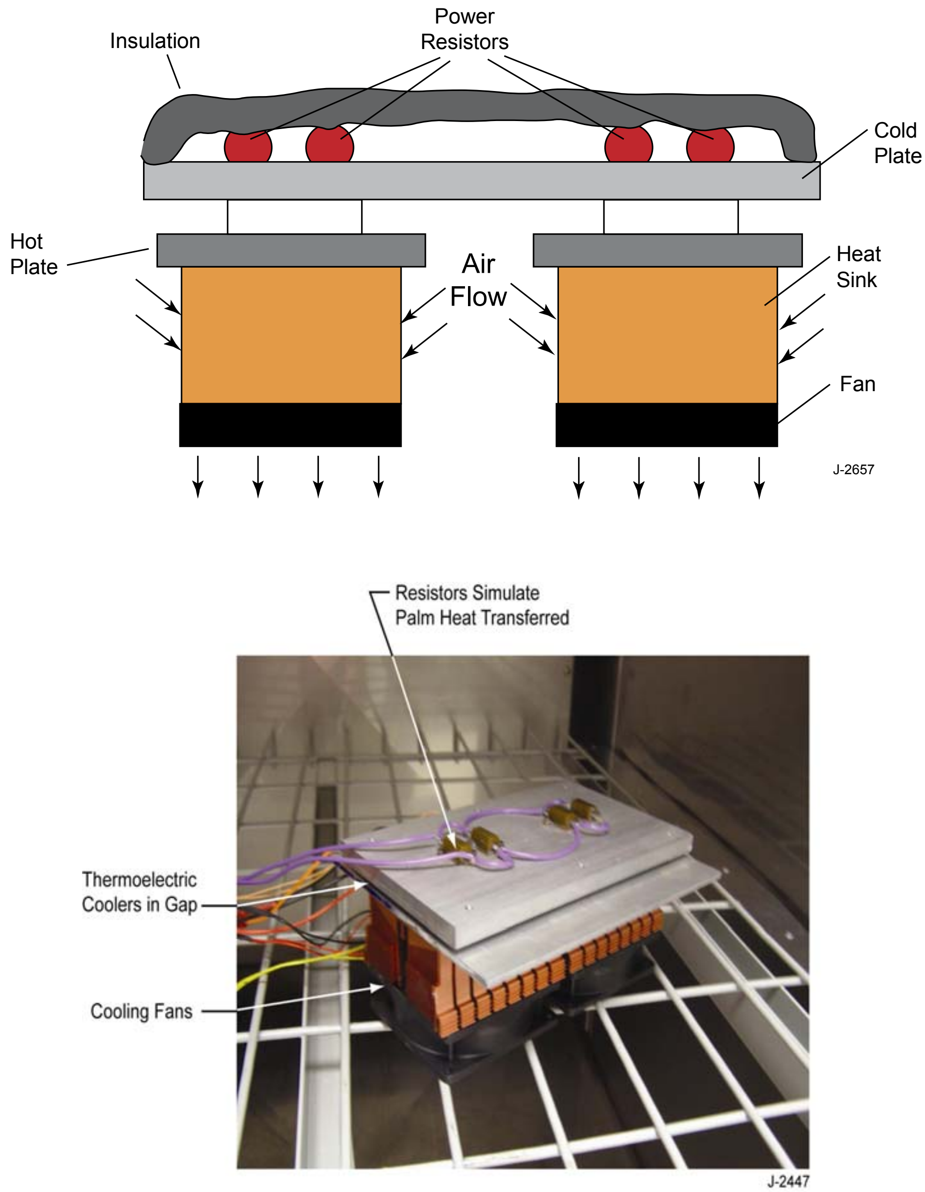

Figure 13. Prototype thermoelectric hand cooler built and tested in this program.

Several improvements should be able to reduce the temperature of the cold plate to 10C in a 40C operating environment. The cooling fans can be improved, the surfaces and plate alignment can be improved, and the loss of heat through the heater clamping screws can be minimized. In the demonstration just described, we achieved only about 50% of the efficiency claimed by the manufacturer's specifications.

6. Conclusions

We have performed both experimental and model-based analysis of a device for removing heat from a hyperthermic soldier. The models show that the heat transfer rates measured both at PSI and Stanford are consistent with physiological parameters.

Our experimental results show that in most cases, the vacuum induces only a modest increase in heat transfer (typically 15%). PSI did measure an increase of more than 100% in one test, and Stanford researchers routinely observe large increases in heat transfer due to the vacuum. It appears that significant heat stress must be achieved to get the benefit of the vacuum. Thus, most of the benefit of hand cooling can be obtained without the vacuum. For short-term cooling of overheated persons, a pair of devices (one for each hand) would provide more total heat transfer than a vacuum-augmented single-hand cooler.

The solid-state cooler design is suitable for installation on an armored transport vehicle. We are currently analyzing how a set of these cooling stations might be deployed. For an 80 Kg soldier with a body core mass of 10 Kg, a 30 W cooler would provide a cooling rate of 3 deg/hr, reducing the adverse thermal effects on soldiers and enhancing their ability to perform their jobs.

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